On Alfvenic waves and stochastic ion heating with 1Re observations of strong field-aligned currents, electric fields, and O^+ ions

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Abstract

The role that the cleft/cusp has in ionosphere/magnetosphere coupling makes it a very dynamic region having similar fundamental processes to those within the auroral regions. With Polar passing through the cusp at 1 Re in the Spring of 1996, we observe a strong correlation between ion heating and broadband band ELF (BBELF) emissions. This commonly observed relationship led to the study of the coupling of large field-aligned currents, bursty electric fields, and the thermal O^+ ions. We demonstrate the role of these measurements to Alfvenic waves and stochastic ion heating. Finally we will show the properties of the resulting density cavities.

1. Introduction

On a moving spacecraft, short wavelength dispersive Alfven Waves (DAW) are Doppler shifted and observed as ELF electromagnetic noise (BB-ELF) over a broad frequency range (typically below 220 Hz). In this paper we follow the plasma properties of the O^+ ion energization with the power in the BBELF waves. In a typical cusp pass at 5100 km, the Polar spacecraft observes the BBELF waves that are commonly coincident with ion energization. Figure 1 shows an example of a typical spectrogram of the BBELF noise from the Polar Plasma Wave Instrument (PWI) (bottom) along with the Polar TIDE O^+ energization (top). A polar contour of the ubiquitous nature of BBELF from PWI in shown in Figure 2a. The largest PSD is observed near 76.8° latitude where the peak O+ temperatures occur (2b). The velocity moments during a typical cusp pass illustrating the density cavities occuring on the temperature gradient are shown in Figure 3.

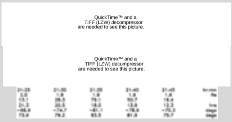

Figure 1. Top panel: Polar TIDE energy/time spectrogram showing typical cusp ion O^+ energy increase from 21:42 to 21:45 in the cusp. Bottom panel: PWI observations of BBELF emissions at this same time.

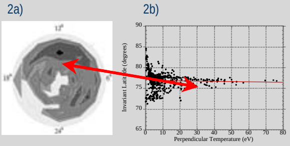

Figure 2a) Contours of PWI electric PSD at 10 Hz frequency band 2b) Invariant latitude as a function of O^+ perp. temperature. The mean invariant latitude is ~76.8°

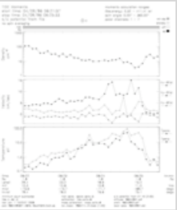

Figure 3. Example of typical moments during the cusp passes. Viewing from equatorward to poleward side (right to left: Temperatures rise steeply on equatorward side and decrease more slowly on the poleward side. Density cavity observed on steep temperature gradient.

2. Ion Heating and Stochastic Ion Heating Rates

The correlation between ion energization and the BBELF power is well known. Figure 4 demonstrates this strong correlation as observed from Polar for the dayside cusp passes at 5100 km. This data consists of » 6000 data points with the O^+ perpendicular temperatures averaged within each PSD bin. The profile at the 5.62 Hz frequency band is similar for the other frequencies profiles in the PWI BBELF range with no structure seen at the gyrofrequency in frequency profiles. The temperatures as a function of the sum of the PSD from 5.6 to 311 kHz is also shown. A threshold is suggested between 10^{-9} and 10^{-8} $V^2/m^2/Hz$ and is analogous to the threshold of 10^{-9} $V^2/m^2/Hz$ at ~1500 km found by Knudsen [1998] during Freja apogee passes.

Although limited in sampling period, the comparison of three different heating rate calculations from measurements for stochastic ion acceleration for a static electric field are shown in Figure 5. Each of the three rates are obtained using Polar measurements. All assume local heating as observed in Section 3 of this paper.

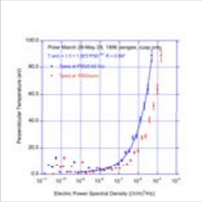

Figure 4. Strong correlation (R=0.997) of averaged O^+ perpendicular temperature as a function of the 5.6 Hz PSD (blue) and the sum of the frequency bands (red).

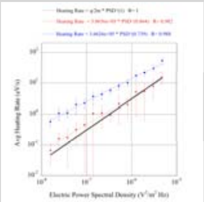

Figure 5. Comparison of heating rate calculations as a function of PSD. TIDE/PWI cusp heating rate measurements (red) and (blue). Comparison to the heating rate for stochastic ion acceleration (black).

Heating Rate (blue) = $dT/dt \approx V_p \cdot E_x$ Staciewicz [2000

Heating Rate (red) = $$dT/dt = \frac{(T_{pf} - T_{po})}{L/V_{perp}} = \frac{(T_{pf} - T_{po})}{(V_{sc} \cdot \Delta t)/V_{perp}}$$

Heating Rate (black) = $$\dot{W}_{\perp}(eV) = \frac{q}{2m}\psi$$

3. Observations, Particles and Fields

For the dayside cusp, BBELF and ion energization is often coincident with large currents and large electric fields perp. to the local magnetic field. Figure 6 shows the Polar/EFI perpendicular electric field (red) coincident with the increase in TIDE O^+ perpendicular temperature (blue) for May 12, 1996. Observations of continuous 90° O^+ ion conics during this same time period indicate that a local ion heating mechanism is in effect (Figure 7).

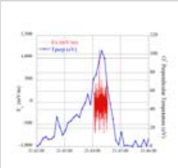

Figure 6. Polar TIDE and EFI observations showing O^+ perp. temperature increase coincident with large perpendicular electric field, E_x.

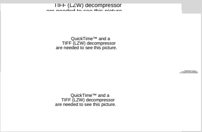

Figure 7. TIDE velocity distributions of 90 ° ion conics during full time period.

4. Observations, Fields

When the perpendicular scale of DAW waves become comparable to the ion gyroradius the wave becomes dispersive and interacts strongly with the particles. Again, these short wavelength DAW are Doppler shifted and observed as ELF electromagnetic noise or BB-ELF. One method of heating the ions when $\omega < \omega_i$ can be explained by stochastic ion heating by these short perpendicular wavelength electrostatic waves [Chaston 2005]. Here we look at signatures of one typical cusp pass provided by Polar/TIDE and EFI and determine through data analysis if the fields are Alfvenic and if the ion heating can be explained by the stochastic process. The ratio of $\delta E/\delta B$ was constructed for spacecraft frequencies below ω_{O^+}. The fluctuations are greater than the Alfven speed of » 10^4 km/s. Figure 8 shows the power spectrum of δE and δB and their ratio as a function of frequency and wavelength in the spacecraft frame.

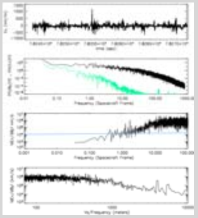

Figure 8.
- 1st panel. High resolution perp. electric field, E_x. Evidence of Alfvenic fluctuations.
- 2nd panel. Power spectrum of electric, $\delta E_{\perp 1}$, and magnetic field, $\delta B_{\perp 2}$, limited to 8 Hz by sampling.
- 3rd panel. $\delta E_{\perp 1}/\delta B_{\perp 2}$ as a function of frequency in the spacecraft frame. V_a = local Alfven speed averaged over the interval shown.
- 4th panel. If the waves are due to DAW we can plot $\delta E_{\perp 1}/\delta B_{\perp 2}$ as a function of wavelength. Vs = spacecraft velocity

Figure 9 shows the perpendicular electric fields with Alfvenic fluctuations and the calculation of $\chi = \delta E/dx\,(\omega_O B_o)^{-1} > 1$. The observed electric field gradients do meet the stochastic ion heating mechanism criteria, $\chi > 1$, for assumed wavelengths of 1921 meters (approximately $4\rho_{O+}$ with 100 eV at 5100 km and lower).

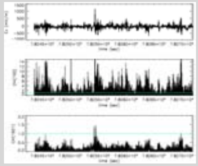

Figure 9. Panel A. High resolution perpendicular electric field, E_x, for May12. Evidence of Alfvenic fluctuations.

Panel B,C. Calculation of electric field gradients reveals $\chi > 1$ for two assumed wavelengths scales; 100 meters (B) and 1921 meters (C). (O^+ 100 eV Larmor radius = 473 meters.)

5. Observations, Density Structures

It was suggested by Chaston [2006] that the width of the density cavities can increase due the production of Alfven waves on the transverse density gradients. Over the narrow cusp passes, we averaged the depth, $(n_0 - n)/n_0$, and the width of the density cavities for each PSD bin. Figure 10 suggests an increase in the density depth from 30% - 60% with increase in PSD. Figure 11 also suggests an increase in the average width of the density cavity from 168 km to 294 km with increase in PSD.

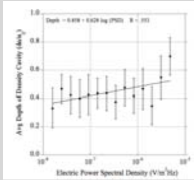

Figure 10. Average density depth as a function of PSD

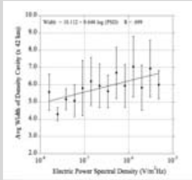

Figure 11. Average width of density cavity as a function of PSD.

6. Summary

Cusp observations are often coincident with strong perpendicular electric field gradients and continuous 90° conics over the narrow cusp passes. We begin by showing that the power observed from BBELF, now thought to be Doppler-shifted short-wavelength DAW, is consistent with stochastic ion heating by turbulent fields. Analysis for a particular Polar pass show Alfvenic fluctuations evident in the perpendicular electric field and that the $\delta E/\delta B$ fluctuations are greater than the local averaged Alfven speed and so the electromagnetic fluctuations are suggestive of Alfven waves. Data analysis shows that the stochastic heating mechanism may be in effect for the cusp at 5100 km. The stochastic heating criteria, $\chi > 1$, is met for scale lengths appropriate for O^+. Although limited by the sampling period, analysis on the density cavitation shows vertical depths ranging from 30-60% and horizontal density cavity widths of ~ 200 km.

7. References

Lotko, JASTP, 2007; Chang, JGR, 1986; Chaston, JGR, 2005; Chaston, JGR, 2006, Staciewicz 2000